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ABSTRACT

Designed to support the premise that many important clues to the solution of the problem of teaching thinking skills in science are contained in the science process skill literature, this paper synthesizes research related to the teaching of science process skills. Studies which evaluate the effect of the new science curricula are described. Specific attention is given to studies which focus on single process skills, comprehensive process skill outcomes, and on formal operational studies which focus on the ability to conduct experiments. The role of computers in teaching process skills is also examined. The reviewed research suggests that thinking in science can be taught and learned by elementary, middle, and secondary students. Implications for instruction are noted and specific suggestions for teachers are offered. These include: (1) matching the teaching tasks and expectations to the level of the learner; (2) working with familiar materials; and (3) teaching efficient problem solving strategies. A 44-item bibliography is included. (ML)

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THINKING IN SCIENCE: THE SCIENCE PROCESS SKILLS

PROBLEM

One of the primary purposes of public education has been the development of the ability to think. In the early sixties, the Educational Policies Commission of the National Education Association (1961) noted that "...the development of the ability to think...is the central purpose to which the school must be oriented..." This purpose is as relevant for the eighties as it was in the sixties.

In science education the development of the ability to think has been stressed as an important outcome for scientifically trained students of all ages. At various times during the history of science education, "critical thinking," "problem solving," and "scientific thinking" were goals emphasized by various professional organizations and science curricula. The National Science Teacher's Association, in an important position statement, declared the development of "individuals with a high competence for rational thought...the major goal of science education..." (NSTA, 1971). Yet, while development of the ability to think has remained a lofty aim over the past twenty years, the actual implementation of this aim has been problematic. What evidence can be collected which speaks to this significant and persistent problem in science education? This question is the focus of this paper.

RATIONALE AND HISTORICAL PERSPECTIVE

What thinking means in the field of science education has varied at different times during the twentieth century. In the early part of the century, a movement to establish the scientific method was the focus of thinking in science. In mid-century, terms such as problem solving and inquiry became more popular for describing thinking in science. More recently, specific skills such as observing, classifying, inferring, or identifying and controlling variables have taken on this role.

Scientific Method

In the period beginning with the 1920's, the major focus of research and writing about thinking in science was the scientific method. Curtis (1924) listed a set of techniques, including locating problems, inventing check experiments, using controls and isolating the experimental factor. Subsequent researchers refined these elements of the method, validating several steps with research scientists.

As the concept of scientific method evolved it engendered much controversy, however. The method did not apply to all science disciplines in the same way, and there were distinctions among various conceptualizations of the method itself. Finally, it was the perceived rigidity of the set of procedural steps in the method that caused it to fall into disfavor (Dressel, 1960).

Problem Solving and Inquiry

In place of the scientific method came more fluid conceptualizations of thinking in science. Problem solving and inquiry were embraced as substitutes for all or parts of the scientific method (Smith, 1963). In addition, other terms, like

"critical thinking," "productive thinking," and "scientific thinking" were introduced and used. Each term emphasized one aspect or another of the earlier formulation identified as the scientific method. However, none of the terms was defined specifically enough for it to be useful as either a teaching or research paradigm. As an example, research on the inquiry approach to teaching and learning proved to be highly unproductive, primarily because each researcher operationally defined "inquiry" in a slightly different way. Thus by the late 1950's and the early 1960's thinking in science was enmeshed in a morass of terminology.

Science Process Skills

A modified and more specific conception of thinking skills in science arose and gradually took hold in the sixties. Termed the science process skills, this conception has become a powerful force in science education over the last 20 years. While it is difficult to identify the precise genesis of the term, present day usage stems in large part from two sources. First, Jerome Bruner wrote The Process of Education (1961) in which he stressed the need for curricula which allow for "solving problems on one's own" and advocated devoting the first two years of school to excercises in manipulating, classifying and ordering objects. In short, Bruner saw "those processes as educational ends in themselves..." (Shulman & Tamir, 1973).

Secondly, the new elementary curriculum, Science - A process approach (S-APA) focused its entire program on skills that scientists used to solve problems. S-APA defined the process skills as a set of broadly transferrable abilities, appropriate to

many science disciplines and reflective of the true behavior of scientists. S-APA divided process skills into two types--basic and integrated. The basic science processes were observing, classifying, communicating, measuring, using space/time relations, using numbers, inferring and predicting. These skills provided a foundation for learning the more complex integrated skills. The integrated science process skills were controlling variables, interpreting data, formulating hypotheses, defining operationally and experimenting (AAAS, 1967).

S-APA fulfilled a need for standardization of terminology within science education by distilling a group of highly complex intellectual activities into a set of relatively well defined process skills. Other new curricula of the era quickly adopted the S-APA list of skills and definitions, including the Biological Sciences Curriculum Study and The Science Curriculum Improvement Study. This agreement on terminology allowed science educators to focus on developing and evaluating the effectiveness of curriculum materials for teaching these thinking skills. It substantially ended the intellectual controversies that had surrounded the conceptualization of scientific thinking.

Some are still critical of certain aspects of the science process skills (e.g. Finley, 1983). While these skills are probably not the perfect expression of scientific thinking, science process skills are fulfilling a need for focusing attention on this aspect of science. And most would agree that this focus is much needed. Students who learn to formulate hypotheses, interpret data, or generalize in the science classroom are more likely to use those skills in other school or real life

situations. As proof of the acceptance of science process skills, the most recent update of the NSTA position statement on science and technology states, "The scientifically literate person has a substantial knowledge base of facts, concepts, conceptual schemes, and process skills which enable the individual to continue to learn and think logically" (emphasis added).

It is the purpose of this paper to propose that many important clues to the solution of the problem of teaching thinking skills in science are contained in the science process skill literature. By reviewing studies which successfully taught the science process skills, much can be learned about thinking in science. Subsequent sections of this paper will explicate this research, will synthesize it, and list several implications for teaching these skills.

RESEARCH DOCUMENTATION

Studies evaluating the effect of the new science curricula will be described first. This will be followed with reviews of studies focusing on single process skills, then with those looking for comprehensive process skill outcomes, and finally with those formal operational studies focusing on the ability to conduct experiments. A last section will briefly outline the potential of the microcomputer.

Effect of New Science Curricula on Process Skills

Because a strong emphasis on process skill abilities was instigated by the curriculum development projects of the 1960's, it is not surprising that much of the process skill research stems from evaluation of these programs. In a meta analysis which summarized the effects of the "new science curricula" on student

performance, Shymansky, Kyle and Alport (1983) reported a strong positive mean effect size (ES=0.61) favoring the new curricula over traditional science on process skill outcomes. An effect size of this magnitude indicates that students exposed to the new science curricula achieved an average 0.61 standard deviations above the traditional curriculum students. The effect sizes ranged from 0.002 for Chemistry to 0.90 in the Biological Sciences (General Science ES=0.59, Earth Science ES=0.22, Physical Science ES=0.08). While these authors defined process skills in rather broad terms (they included all "lab skills" under this term), their results indicate a general superiority for the new curricula.

When individual studies which evaluated specific science curricula are examined, a greater amount of detail can be gathered as to the effectiveness of programs in teaching science process skills. Several studies compared the Science Curriculum Improvement Study (SCIS) to traditional curricula and almost all found SCIS successful at teaching process skills. In retrospect it is not surprising that SCIS students outscored control students on process skill outcomes, since SCIS introduces process skills early and allows students many opportunities for practice and transfer. For example, Allen (1973) compared SCIS and control third graders on the abilities of identifying variables in a simple mechanical system and recognizing change in an experiment. SCIS students study these particular topics extensively during the third grade unit Subsystems and Variables. He found students who had experienced SCIS significantly better at both skills. Likewise, Weber and Renner (1972) and Boyer and Linn (1978)

identified groups of students who had experienced equal number of years of SCIS or of a textbook science program. Weber and Renner compared their students on 34 tasks which assessed their abilities to observe, measure, classify, experiment, interpret and predict. Boyer and Linn compared students on the abilities of naming variables and analyzing experiments. Highly significant differences favoring the SCIS children were found in both studies.

A bit surprising is the lack of studies comparing Science - A Process Approach (S-APA) students to controls on process skill outcomes. Considering that the major goal of S-APA was to produce process skill outcomes, one would expect a reasonable amount of evaluation related to this goal. However, program developers were more interested in determining whether subjects were achieving the specific process skill outcomes (Walbesser and Carter, 1968; Torop, 1971), than contrasting S-APA to other curriculum approaches. Two comparative studies that were identified, however, and both favored S-APA subjects. After contrasting over 500 third through sixth grade S-APA students to those in a traditional science course, Wideen (1975) concluded that "the success of S-APA as compared to traditional science teaching clearly lies in the area of improving...process oriented skills." Results with kindergarten and first grade subjects (McGlathery, 1970) are in substantial agreement.

At the secondary level, studies evaluating the effects of specific curriculum projects on process skills were generally disappointing. Three studies reported process skill outcomes in their evaluations of Patterns and Processes (Stronck, 1971), Introductory Physical Science (Butzow and Sewell, 1972), or

Invitations to Enquiry (Starr, 1972). Lack of significant differences, perhaps resulting from weak research designs, limits the importance of these works, however.

Single Process Skill Outcome Studies

Several researchers constructed experimental treatments to teach individual process skills. In general these studies showed that behavior relative to an individual skill, such as hypothesizing, can be taught and is usually retained. For example, Quinn and George (1975) built on the work of Atkin (1958) who had described children's hypothesizing abilities. They employed a method devised by Richard Suchman (1966) in which film loops displaying different discrepant events were shown. For instance, one film loop shows an ice cube floating in one beaker of water but sinking in another. Students were taught to ask questions and form hypotheses about these discrepant events. Compared to a control, the treatment groups wrote significantly higher quality hypotheses after 18 training sessions. The authors concluded that hypohtesis formation can be taught using a combination of inquiry training and discussion techniques.

Other studies of this type proved useful because of the thoughtful micro-analysis of the specific skill being studied. For example, Thiel and George (1976) investigated the relative effectiveness of rules on the predicting behavior of third, fourth and fifth graders. While no significant differences were found, this study proved to be important because the authors not only described and defined terms precisely, but also considered the developmental abilities of subjects as a potentially important

variable. This study and several others provide a sound basis for further research in this area.

At the secondary level, the single most commonly investigated process skill was hypothesizing. Results from several studies confirmed that this skill can be effectively taught in a regular classroom. Wright (1981) extended the work of Quinn and George (1975). He compared a control group to treatments which used film loops of discrepant events plus intensive instruction on either observing details or hypothesis generation. He found the treatments equal and significantly better than the control on the number and quality of hypotheses generated by students on post and retention tests. This work was later expanded and tested by Pouler and Wright (1980) with similar results.

Tomera (1974) investigated the transfer and retention of observation and comparison skills in seventh grade students. Each treatment used similar methods including explanation of the processes, practice with objects, class discussions, drawings, and evaluative feedback. She found that both skills can be taught using this procedure and that transfer to new objects and across time was exhibited.

Comprehensive Process Skill Outcome Studies

While many researchers concentrated on single process skills, others focused on outcomes involving several different process skills. Macbeth (1974) investigated the effect of manipulating concrete materials on the process skill outcomes of kindergarten and third graders. Students experienced lessons in pairs with one being designated as the materials manipulator, while the other was given various nonmanipulative tasks. Results indicated that for

kindergarten children, the manipulative treatment produced higher process skill outcomes. However, no differences were found for third graders. This study indicates that manipulation of objects may not always provide a more effective learning environment. Viewing the manipulations may suffice for some children, at certain ages, and with certain process skills.

Two papers examined the effects of incorporating process skill activities into the regular secondary science curriculum. Peterson (1978) compared two types of training to a placebo group. He constrasted "hands-on" inquiry training similar to that described by Suchman (1966), to an Ausubelian type of verbal inquiry, to a placebo group which experienced two Project Physics units. Both treatments were supplemental to the regular Project Physics work. On a process skills posttest he found both the "hands-on" training and the verbal inquiry training better than just the regular Project Physics curriculum. He concluded that "the value of focused and specific training in scientific inquiry" is worthwhile even in addition to a curriculum purported to teach process skills. Padilla, Okey and Garrard (in press) tested the effects of systematically integrating science process lessons into a middle school science curriculum. They compared the effectiveness of three treatments. One emphasized a two week introductory unit on designing and carrying out experiments. The second taught the same two week unit but added one process skill lesson per week for a period of fourteen weeks. The third was a control. Students in treatment two signficantly outscored the other two groups on an integrated process skills test. The authors concluded that a single two week process skills unit might

not be most effective for process skill training. Students seem to need continued, related practice in order to master the integrated processes.

Science Process Skills and Formal Operations

A more recent development in the Science Education literature is the intense interest in formal operational abilities. Noteworthy among these abilities is what Inhelder and Piaget (1958) call controlling variables. In essence this label describes the process of designing and conducting a controlled experiment so that certain problem related generalizations can be drawn. These are substantially the same abilities encompassed by the integrated process skills as defined by S-APA. This logical connection has been confirmed by Padilla, Okey and Dillashaw (1983) who found an overall correlation of .73 between the two sets of abilities.

The main impact of this relationship is that the somewhat richer theoretical base of formal operational research can be used to better understand integrated process skills abilities. But with this rich theoretical base comes the knowledge that many recent studies (c.f., Chiapetta, 1976) show even high school students not able to control variables in certain situations. Can training students in these abilities result in student mastery?

Two studies developed treatments which were classroom oriented and group administered. Case and Fry (1973) taught 15 low SES, fourteen year olds to plan controlled experiments by having them design, conduct and critique experiments. After twelve 40 minute sessions over as many weeks, they found the treatment group significantly better than a matched control on

written tasks dealing with designing experiments and experimental control. Howe and Mierzwa (1977) designed a treatment centered on a cognitive conflict strategy in which students were confronted with situations "which were puzzling or seemed illogical." They were subsequently encouraged to interact with each other and were provided with opportunities to resolve the conflict. The focus of this treatment was the development of a controlled experiment. Treatment students outperformed controls on the posttest (two controlling variables tasks) and on a retention test (one controlling variable task). Most unique about this study was that it not only attempted to develop a treatment that could be used in regular science classrooms, but it also was alone among formal operations studies in finding significant differences on a retention test.

Several studies investigated treatments of short duration (less than five hours) and/or ones in which individual training was used. Wollman and Lawson (1977) for example, trained fifth and seventh graders individually in three to four sessions of 30 minutes duration. Trainers used simple experiments, "think aloud" techniques, and adopted the role of someone who knew nothing. They found experimental students better able to control variables on both interview and written posttests than control students.

Other studies which tried to teach experimenting abilities found only minimal success. Reasons for lack of experimental differences vary but include very strict requirements for a response to be considered correct (Lawson, Blake and Nordland, 1975), insufficient sample size (Bredderman, 1973), poor

evaluation instruments, and treatments not powerful enough to effect change.

Using computers to teach process skills

Until recently the cost of implementing computers in education has been beyond the means of most school districts. Today the microcomputer has changed that picture dramatically. A recent NSF projection estimates that one million microprocessors will be in elementary and secondary schools by 1985 (Gleason, 1981). It seems logical that this new learning tool be applied to learning important skills such as the science process skills.

One of the most promising uses of computers involves problem solving simulations in which the computer models a real world situation. The student makes decisions based on data collected from these situations and observes the consequences of the decisions. The capacity of the computer to branch students to different program or feedback sections, depending on student response, makes this tool quite powerful.

Simulations have been used widely in many areas for teaching specific skills such as those required by astronauts and pilots. In science education some of the main-frame computer programs on the PLATO system are good examples of simulations. In the famous fractional distillation lesson on that system, for example, students can distill a complex mixture of organic compounds without worry for lab equipment or safety. Wise (1983) used microcomputer based simulations of electrical circuits to successfully teach ninth grade students concepts like series and parallel circuits. There is no reason why simulations of science

process skill lessons wouldn't be just as successful. To this date no research on the specific topic has been reported, however.

SYNTHESIS OF STUDIES

The studies reviewed in this paper offer promise to science educators. Several reported that basic and integrated process skill abilities can be improved through experience with specific curricula or by using various teaching methods.

Research which evaluated the effect of the SCIS and S-APA elementary curricula indicates that these two projects, which specifically aim to teach process skill abilities, are generally successful in doing so. Little worthwhile research of this type with the secondary programs has been reported. One could only hypothesize that these programs, whose main goal is to teach subject matter knowledge and only secondarily emphasize process skill abilities, may not be very successful at inculcating process skills. An insightful analysis by Herron (1971) of the Physical Science Study Curriculum (PSSC) and the Biological Sciences Curriculum Study (BSCS) showed that most of the lab activities (approximately 75%) in both programs are at a level where the problem, the procedures, and the answers, are specified. Only 4% of PSSC and 6% of BSCS activities asked the students to design their own procedures for solving a given problem. Thus, it would not be surprising if these and other highly regarded secondary programs were less adequate in developing the process skills involved in experimenting than many science educators and teachers expect. This doesn't mean that these programs do not improve abilities in the basic process skills, however. This contention has yet to be fully tested.

Studies by Peterson (1978) and Padilla, et al., (in press) signify that even if the curriculum does not teach process skill abilities, the addition or integration of specific process skill activities into regular classroom work can have important positive effects. The indication is that classroom teachers can add a relatively short unit on conducting a fair experiment followed by weekly practice sessions and that this will increase students' integrated process skill abilities. Padilla, et al., even contend that these activities can often be based on the science content normally covered by the teacher. Thus, these lessons need not be taught instead of content lessons. It is possible for both sets of goals to be accomplished simultaneously.

Classroom treatments based on Suchman's (1966) Inquiry Development Program and using discrepant events have proven quite successful in training both elementary and secondary students to hypothesize. Teachers and researchers should re-examine this model as a means for training students on other integrated process skills. Techniques for controlling variables, interpreting data, defining operationally and experimenting could be taught using the discrepant event model.

The literature on formal operational abilities has cast the acquisition of integrated process skills in a new developmental light. This different point of view is important because it strongly suggests that teachers may not be able to teach every student to conduct well controlled experiments. Instead both teachrs and researchers need to begin to understand how developmentally related abilities are gained. Inhelder and Piaget (1958) propose that gains "depend on three principal factors:

maturation of the nervous system, experience acquired in interaction with the physical environment, and the influence of the social milieau." Obviously, little can be done to make the nervous system mature faster. Science educators need to realize that some students will have problems with difficult cognitive tasks like those involved in the integrated process skills. On the other hand the teacher can control the students' experiences with the physical environment, and the school is an important part of the social milieau. By planning learning activities that stress interaction with the physical environment and by structuring the school environment to facilitate the learning of complex cognitive tasks, teachers can maximize the possibilities of gains on the integrated process skills.

Finally, the potential for microcomputers becoming an effective tool for teaching science process skills is very high. While little research has been reported to date, experience with main frame systems indicates they can be quite successful.

Implications for Teaching Science Process Skills

What specific suggestions for classroom teachers and science educators do the reviewed studies imply? Three components of classroom activities seem to have promise: 1) Matching the teaching tasks and expectations to the level of the learner, 2) working with familiar materials and, 3) teaching efficient problem solving strategies.

Clearly, classroom teachers can be successful in teaching experimenting abilities if the learning activities are appropriately matched to the learner. Wollman and Lawson (1977) indicate that the basis for conducting a controlled experiment is

evident even among very young elementary school children, many of whom have "a sound intuitive understanding of a fair test." Thus, it is not surprising that Allen (1973), Weber and Renner (1972) and Boyer and Linn (1978) reported gains on integrated process skill achievement for subjects who experienced the SCIS program. In dealing with controlling variables and experimentation, SCIS begins simply, at the level of the young learner and with activities having a limited number of variables. Likewise, the researchers in their assessment of program effects did not expect the students to perform at the level of high school students. Instead evaluation tasks were aimed at the level of the instruction and the developmental level of the learner.

Materials related variables are often important to the acquisition of integrated process skills. Levine and Linn (1977) state that familiarity with the variables in the learning or assessment tasks is important to task performance. The more familiar the variable, the more likely is success. They also suggest that the number of variables influences difficulty. The more variables involved in a given task, the more difficult the task. Thus, regardless of the age of students, teachers should begin integrated process skill instruction with familiar materials and should restrict the number of variables in activities.

Science teaching strategies which help students with organizational or learning strategies appear to show promise for teaching integrated process skills. Instructing students to be systematic in their collection of data or use of written records and charts was one part of the effective treatment devised by Padilla, et al., (in press). Lawson and Wollman (1976) provided

the symbolic notation of "fair" and "unfair" tests that helped students classify experiments in their minds. General learning strategies like "making all things equal," which help students simplify complex problems, have also been successfully used (Lawson and Wollman, 1976). Levine and Linn (1977) summarize the importance of strategies by stating:

> Clearly, whether the problem solver has an imprecise strategy or has difficulty simplifying the problems to fit a strategy, the result will be failure on the problem. Strategies can be learned for simple problems. Once the strategy is learned, procedures for simplification of complex problems to fit the strategy can be developed. It might be that generalized strategies for simplifying problems are developed by successful learners (p. 380).

Summary and Conclusions

This paper has concentrated on the problem of teaching students to think in science. The science process skills have been proposed as a solution to this problem. Research related to different process skills has been reviewed and most of the studies indicate that, within certain limits, thinking in science can be taught and learned by elementary, middle and secondary students. This message needs to be communicated to science teachers in the field.

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